Radiometric force in dusty plasmas

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Abstract

A radiofrequency glow discharge plasma, which is polluted with a certain number of dusty grains, is studied. In addition to various dusty plasma phenomena, several specific colloidal effects should be considered. We focus on radiometric forces, which are caused by inhomogeneous temperature distribution. Aside from thermophoresis, the role of temperature distribution in dusty plasmas is an open question. It is shown that inhomogeneous heating of the grain by ion flows results in a new photophoresis like force, which is specific for dusty discharges. This radiometric force can be observable under conditions of recent microgravity experiments.

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Numerous industrial applications, such as material proceeding, has triggered active research on the phenomena associated with dust dynamics in a low-pressure glow discharge. A dusty plasma [1, 2] is formed by introducing micron-sized grains in a plasma. The grains are negatively charged due to the higher mobility of electrons with respect to ions. Then the medium is composed of particles with fixed charge (electrons and ions) and variable charge (dust grains). Typically, the microspheres can be easily charged to $10^4 - 10^5$ electron charges. In a low-temperature radiofrequency discharge the grains usually remain electrically suspended in the sheath above the electrodes [3]. Here the gravity is exactly balanced by the electric force. The grains form ordered lattice structures, known as Coulomb crystals.

The plasma boundary near the electrodes is characterized by highly non-equilibrium conditions. In particular, the grains undergo a supersonic (Bohm criterion) ion flow, resulting both in an ion drag force and specific attractive forces between the grains [4]. The neutral gas causes an important additional class of forces, which are related to the density and temperature gradients. Aside from thermophoresis [5, 6] the role of such forces is an open question. In this rapid communication we focus on a radiometric forces. We found that ion flows result in inhomogeneous temperature distribution of the grain surface. Then the interaction with the neutral gas results in a force similar to photophoresis [7], but it is provided by a plasma recombination at the grain surface.

Let Q denote the energy released in each act of ion recombination. Typically, the value of Q is of the order of ten eV. We assume that this energy is absorbed by the grain and results in the heating of its surface. Recall that the ion flow in the sheath near the electrodes is strongly non-isotropic. The widely spread approximation is that zero-temperature ions move towards the electrode with the same supersonic velocity Mc_s, where $M > 1$ is Mach number, and c_s is the ion sound velocity. Then the energy flux per a unit square of the grain surface oriented normally to ion velocity, can be estimated as

$$J_0 = \alpha n_i M c_s Q, \tag{1}$$

where n_i is the ion number density and dimensionless factor α takes into account the attraction of ions with the negatively charged microsphere. This will increase the resulting ion flux. Typically $\alpha \approx 2$.

The steady energy flux affects only one side of the grain resulting in some inhomogeneous heating. The stationary temperature distribution inside the grain can be evaluated by means of the the Fourier's equation

$$\mathrm{div}\left[\kappa \,\mathrm{grad}\, T(\mathbf{r})\right] = 0, \tag{2}$$

where κ is the grain thermal conductivity. Eq.(2) should be supplemented with a boundary condition. We characterize the grain surface by a unit vector $\mathbf{n}$ directed outwards. The boundary condition reads

$$J_s = \kappa \left(\frac{\partial T}{\partial \mathbf{n}}\right)_s + \sigma(T_s - T_0), \tag{3}$$

where the subscribe s recalls that this equation is applied to the grain's surface only. The function J_s is an external energy flow onto the grain, which is caused by the recombination. The first term in the right-hand side of Eq.(3) represents the energy flow in the interior of the grain. We emphasize that the the grain permanently interacts with the neutral gas, which is assumed to be uniform, with some temperature T_0 differing from the grain's surface temperature T_s. The interaction results in heat transfer, which is described by the second term in the right-hand side of Eq.(3). The rate of this natural cooling is characterized by the factor σ.

For a microsphere suspended above the electrode the external energy flow is taken in the form

$$J_s = \begin{cases} -\mathbf{J_0 n} & \text{for top half,} \\ 0 & \text{for bottom half.} \end{cases} \tag{4}$$

Eqs. (2-4) provide a complete description of the temperature distribution inside the gain. For a uniform spherical grain they are readily solvable in terms of Legendre polynomials.

To proceed it is necessary to specify the collision of the neutral molecule with a grain surface. We undertake the assumption of complete energy accomodation. Typically the size of a grain is small, as compared to the mean free path of the neutral molecule. Then the particle distribution in the vicinity of the grain can be taken as a combination of two Maxwell functions:

$$f(\mathbf{r}, \mathbf{v}) = \begin{cases} f_M(T_0) & \text{for } \mathbf{nv} < 0, \\ f_M(T_s) & \text{for } \mathbf{nv} > 0. \end{cases} \tag{5}$$

In should be noted that the number density of the neutral particles moving towards and outwards the grain (n_0 and n_s respectfully) is different $n_0\sqrt{T}_0 = n_s\sqrt{T}_s$ in according to the conservation of the particle flux. Using Eq.(5) one obtains

$$\sigma = n_0\sqrt{\frac{2T_0}{\pi m}},$$

as well as the neutral gas pressure

$$P = \frac{1}{2}n_0\sqrt{T_0}(\sqrt{T_0} + \sqrt{T_s}),$$

where n_0 is identical to the number density of the neutral gas.

Note, that the pressure depends on the local surface temperature. Due to the inhomogeneous temperature distribution the interaction with the neutral gas results in a force expressed as the integral

$$\mathbf{F} = \iint (-P\mathbf{n})\, dS$$

over the grain surface.

In a case of a uniform spherical particle the integration can be carried out analytically. The cumbersome final expression simplifies greatly in the ultimate case of $T_s - T_0 \ll T_0$, which is the only of interest here. The resulting force takes the form

$$F = \frac{\pi R^2 n_0 J_0}{6\left(\sigma + \dfrac{\kappa}{R}\right)}, \tag{6}$$

where R is a radius of a microsphere.

Eq.(6) closely resembles the known relation for the photophoresis force [7, 8]. The difference is due the different physical meaning of the term J_0. In the case of the photophoresis the inhomogeneous heating is a result of external radiation. In a dusty plasma the force results from the ion recombination.

In some experiments [9] the dusty specie is formed by relatively big coreless grains. Let the inner radius of that hollow microsphere be ϵR with constant $\epsilon < 1$. Assuming that the energy flux through the inner surface is negligibly small one can easily obtain the following more general expression

$$F = \frac{1}{6}\frac{\pi R^2 n_0 J_0}{\sigma(1 + \frac{1}{2}\epsilon^3) + \dfrac{\kappa}{R}(1 - \epsilon^3)}. \tag{7}$$

For typical conditions of dust dynamics the first term in the denominator of Eq.(7) is small as compared to the second term. Then

$$F = \frac{\pi R^3 n_0 J_0}{6\kappa(1 - \epsilon^3)}. \tag{8}$$

The ratio of this radiometric force to gravity is independent of the radius of the grain. Generally, it is extremely small. Let us compare the radiometric force with the ion-drag force, which is believed to play an important role under conditions of recent microgravity experiments with dusty plasmas [10].

The ion-drag force is estimated as $F_{\rm drag} = \alpha\pi R^2 n_i m_i (Mc_s)^2$, where the physical meaning of factor α is identical with that in Eq.(1). Hence

$$\frac{F}{F_{\rm drag}} = \frac{Rn_0Q}{6\kappa m_i M c_s(1-\epsilon^3)}.$$

Typically $M \approx 1$, electron temperature $T_e = 2.5$ eV, $Q = 15.8$ eV (Argon), and $\kappa \approx 10^{-2}$ Wt/cm·grad (glasses). We take $n_0 = 10^{16}$ cm^{-3}, and $1-\epsilon^3 = 1/30$. Then $F/F_{drag} = 1$ if $R = 10^{-2}$ cm. The effect therefore should be observable for relatively large hollow dusty grains under microgravity conditions.

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